TIME TRANSFER TEST RESULTS USING THE INMARSAT GEOSTATIONARY OVERLAY

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BIOGRAPHIES

ALISON BROWN

Alison Brown is the President of NAVSYS Corporation, which specializes in developing GPS technology. She has 15 years experience in GPS receiver design and has seven GPS related patents. She has published numerous technical papers on GPS applications and is on the editorial board for GPS World and GIS World magazines. Dr. Brown is currently the Space Representative for the ION Council and Vice Chair for the IEEE Pikes Peak Section.

THOMAS M. KELECY

Tom Kelecy is a Senior Engineer at NAVSYS Corporation, in Colorado Springs, CO, where he is involved with GPS navigation systems design and analysis. Dr. Kelecy has worked in the area of kinematic GPS and orbit determination for the past seven years. Prior to NAVSYS, he was employed as a geodesist for NOAA, where he worked on GPS kinematic positioning techniques for geodetic and oceanographic applications. As a guidance and control engineer with Martin Marietta Aerospace, he contributed to the design and analysis of the attitude determination and control system for the Magellan spacecraft now orbiting Venus. Dr. Kelecy holds a PhD in Aerospace Engineering from the University of Colorado at Boulder, MS from the Colorado School of Mines, BS from the College of Charleston, SC, and AS in Architectural Engineering from Trident Technical College, Charleston, SC.

DICK DAVIS

Mr. Davis recently retired after 40 years of government service and 25 years as an electronics engineer with NIST/NBS time and frequency division. He was primary design engineer on several NIST time and frequency dissemination systems, including the model for a closed captioning system currently that is used for the deaf and hearing impaired, the "GOES" satellite time system, and the "ACTS" automated computer time service, a dial up modem service. The NBS/GPS common view time transfer receiver designed by Mr. Davis became the standard for international time/ frequency transfer at the 10 nsec level. Over 500 receivers based on this design are currently in use for precise time transfer. Mr. Davis is currently working as a T/F consultant.

RICK WALTON

Rick Walton is Director, Service Development in COMSAT Mobile Communications Land Mobile and Special Services Group. He has 17 years experience in satellite communications systems engineering, including earth stations, design, communications equipment for both fixed and mobile applications, and satellite design, fabrication and testing. As director of COMSAT's London office, Mr. Walton worked with INMARSAT on mobile communication systems and services, including the INMARSAT-III spacecraft technical requirements. He is currently responsible for the development of technical solutions of land mobile customers' communications requirements through INMARSAT. Mr. Walton received a BSEE from Lehigh University and an MSEE in Communications Engineering from George Washington University. He is a member of the RTCA Working Group on Wide Area DGPS and Integrity and has co-authored several papers on the INMARSAT-III navigation transponders.

ABSTRACT

INMARSAT has designed a GPS (L1) transponder that will be included in their third generation satellites. This transponder will broadcast a pseudo-GPS signal that can be used for navigation and also for disseminating integrity data or differential corrections for the GPS satellites. This INMARSAT Geostationary Overlay (IGO) service will be used to enhance the performance of the GPS navigation service for civil aviation and other users.

NAVSYS has developed a ground station for the IGO satellite to generate the pseudo-GPS signal that is relayed through the transponder. The ground station includes a closed-loop control mechanism that allows the IGO signal broadcast by the satellite to be precisely synchronized to an external UTC time reference. This capability allows the IGO signal to be used for disseminating precise time on a global basis. By synchronizing the IGO signal to UTC, the navigation performance of the IGO service is also improved by eliminating any degradation from GPS selective availability errors on the IGO signal.

The IGO service has the capability to provide better timing accuracy than any of the existing broadcast time services. Since the IGO signal is compatible with GPS, conventional GPS timing receivers can easily be

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modified to utilize the proposed service. The redundant global coverage provided by the INMARSAT-III satellites will provide the capability for disseminating a precise UTC time reference worldwide.

A test program is being conducted with the cooperation of the National Institute of Standards and Technology (NIST) in Boulder, CO. The IGO signal broadcast by the FAA test-bed is synchronized to UTC using an HP 5071A cesium standard. The pseudo-range to the satellite is monitored at NIST using a GPS receiver that is synchronized to a UTC primary frequency standard. Data collected at the IGO Earth Station in Southbury, CT, is processed with the monitor station data to demonstrate the timing precision possible. Test results from this experiment are included in the paper.

INTRODUCTION

The INMARSAT-III constellation of four geostationary satellites will provide redundant coverage over most of the earth, as illustrated in Figure 1 .

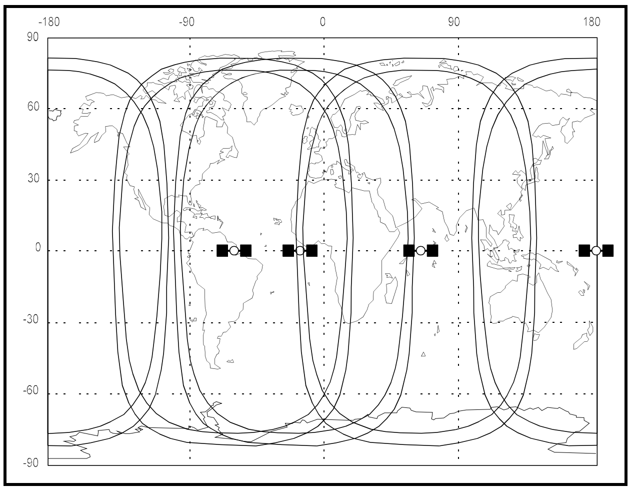

Figure 1 INMARSAT Satellite Coverage

In addition to the communications payload, the INMARSAT-III satellites will also carry a specialized navigation transponder that will be used to broadcast simulated GPS-like signals at the GPS L1 (1575.42 MHz) frequency. This simulated GPS broadcast, the INMARSAT Geostationary Overlay (IGO), can be received by GPS receivers with only slight software modifications. The IGO will provide an additional satellite signal that can be used for navigation, thereby improving the available GPS and GLONASS satellite coverage. Another major motivation for the IGO is the requirement expressed by the aviation community for a GPS Integrity Channel (GIC). The GIC integrity data will be broadcast through the IGO as a navigation message modulated on the simulated GPS signal.

The IGO signal will be generated at specifically established satellite earth stations. It will be controlled so that the IGO signal broadcast by the satellite will appear to be synchronized with the GPS satellite signals. It is also possible to use this architecture to precisely synchronize the IGO signal to a time reference. Since only a single satellite signal is required for precise time dissemination at fixed installations, the four INMARSAT-III satellites can also provide redundant worldwide coverage for precise time dissemination.

Key to the effective use of the IGO are the calibration of the signal timing to a standard time reference such as UTC and accurate knowledge of the INMARSAT satellite orbits. Applications using the signals for navigation and precise time transfer require the orbital position be known to an accuracy consistent with the known accuracy of the GPS satellites. The goal is to eventually be able to determine the INMARSAT orbital positions to meter-level or better.

INMARSAT has ordered four INMARSAT-III satellites which will include C-to-L1 transponders and C-to-C band transponders (for atmospheric corrections). Contracts for all four spacecraft launches have been signed, with the first launch scheduled for June 1995.

SOUTHBURY EARTH STATION EQUIPMENT

The IGO SIGGEN system was designed and built by NAVSYS to provide precise synchronization of the IGO signal to an external time reference. The system components include a Communication Server, a Precision Time and Frequency Reference, SIGGEN Controller, and SIGGEN Monitor.

SIGGEN Communication Server

The FAA is developing a network of ground-based reference stations which will be used to continuously monitor the status of the GPS satellites and generate differential corrections for the observed range errors. This data is processed at a central facility to generate a GPS Integrity Broadcast (GIB) message for transmission by the IGO. The function of the communication server is to continuously receive the GIB message from the FAA central facility and then pass this data to the SIGGEN controller for modulation on the IGO signal.

SIGGEN Precision Time and Frequency Reference

The SIGGEN time and frequency reference provides the time standard to which the IGO signal is synchronized. In the initial test phase, an HP 5071A primary frequency standard has been provided on loan by Hewlett Packard. The HP 5071A clock includes an improved cesium beam tube design that results in an accuracy of $\pm 2\times10^{-12}$. The HP clock was operated during the calibration phase under remote control from NAVSYS using monitor data collected at NIST to adjust the reference for time offset and to keep it synchronized with NIST's UTC time standard.

SIGGEN Controller

The purpose of the SIGGEN controller is to generate the IGO signal and control its timing relative to the SIGGEN precision time reference. The IGO signal is steered so that the timing elements of the signal (the C/A code and data epochs) appear to be synchronous with the SIGGEN time reference when they are transmitted by the INMARSAT-III satellite. In order to achieve this, the signal output by the SIGGEN controller must be advanced in time to compensate for the delays on the up-link path through the satellite transponder.

SIGGEN Monitor

In order to dynamically compensate for the group delays and frequency offsets, the SIGGEN monitor is used to measure the time and frequency offsets of the received signal relative to the SIGGEN time and frequency reference.

UTC TIME SYNCHRONIZATION PROCEDURES

Figure 2 illustrates the synchronization control loop which was used to control and monitor the UTC time synchronization process.

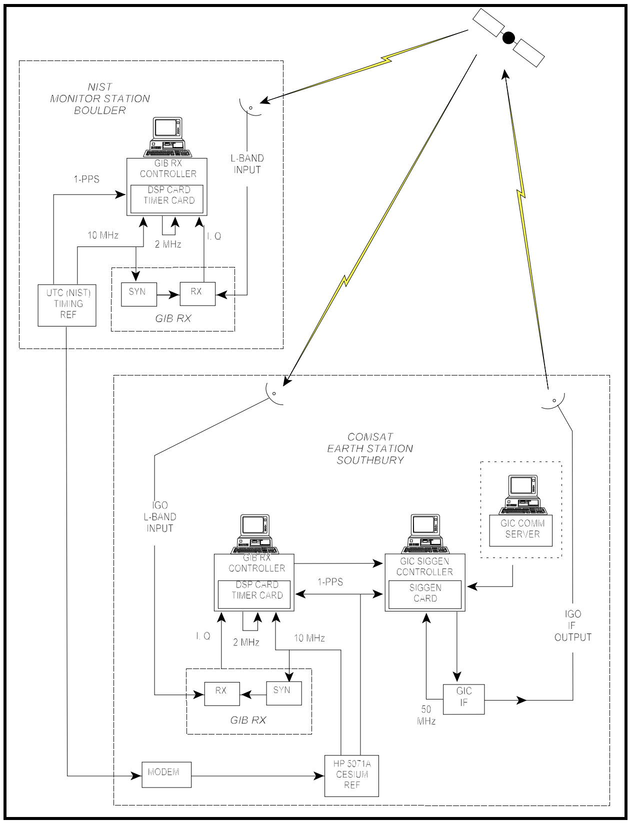

Figure 2 Test Configuration

The SIGGEN IGO signal is driven by the HP 5071A cesium reference at the Earth Station. The goal was to synchronize the HP clock to UTC time so that the ranging information produced by the SIGGEN can be used for GPS integrity monitoring, navigation, and time transfer applications. The highly accurate HP clock was calibrated to the UTC (NIST) time reference by resetting the clock using discrete time adjustments. This required a modem connection between the NIST clock and the HP.

When the HP clock at the Earth Station was adjusted, the pseudo-range being monitored at NIST was compared to a computed range based on predicted INMARSAT satellite orbital elements and NIST coordinates. The offset between the measured and computed ranges represents the clock offset between the HP and NIST clocks. Based on this offset, clock adjustments were transmitted from NIST to the HP via the modem connection and the clock offset was again observed. This procedure was continued until the offset was reduced to some small value. The achievable synchronization accuracy depends on the data quality (noise level) and the accuracy of the computed INMARSAT satellite ranges at NIST. If the satellite ephemerides are accurate to several hundred meters, then a clock closure of less than one microsecond can be expected. If knowledge of the satellite position is no better than several kilometers, then the clock offset can be determined to no better than several microseconds.

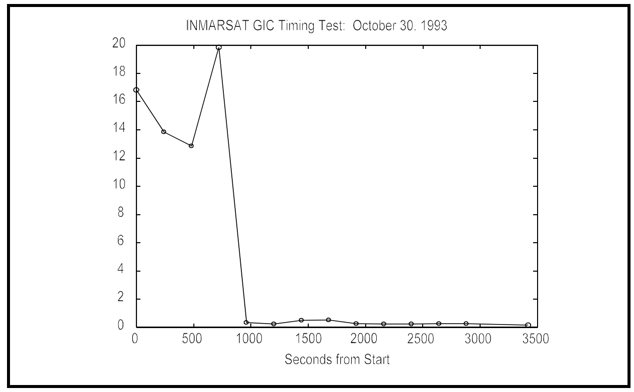

Figure 3 Initial Clock Offsets, October 24, 1993

Figure 3 illustrates the clock offsets between the UTC time standard at NIST and the HP clock at Southbury during this calibration. The offset converged to less than 1 msec by the fourth adjustment, and the final adjustment brought the offset to around .01 msec. No further adjustments were attempted, since the computed INMARSAT ranges were believed to be of limited accuracy due to the age of the ephemeris data and the inaccuracies in the exact time of satellite position determination.

SIGGEN CODE AND CARRIER COHERENCY

The SIGGEN includes the capability to precisely synchronize the code and carrier broadcast from the satellite. The code and carrier coherency for a 3.5-day data set collected at the NIST Monitor Station is shown in Figure 4. The pseudo-range+ carrier phase coherency has a standard deviation of 1103 m (5644 cycles) while the rate has a standard deviation of 0.10 m/s (0.5118 Hz). At this point, the software required to phase-lock the carrier to the code has not been enabled. However, the data plotted in the figure does demonstrate that the frequency lock is maintained between the code and carrier, confirming the successful implementation of the software changes. Further testing will be performed at a later stage to optimize the phase and frequency lock.

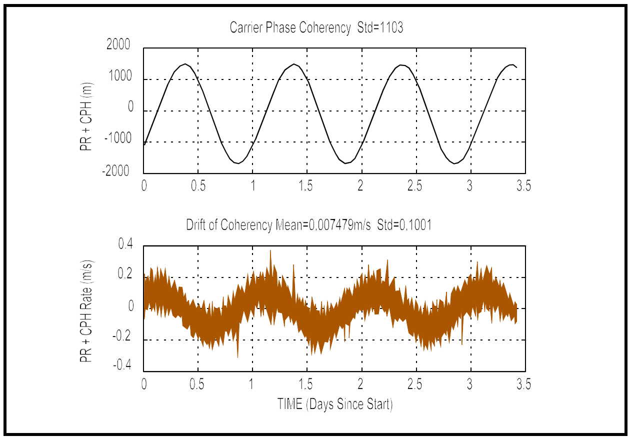

Figure 4 Code and Carrier Coherency

PRECISE UTC TIME SYNCHRONIZATION

The IGO signal from the INMARSAT AOR-West satellite was used for the precise synchronization of the HP 5071A to UTC (NIST). The satellite ephemeris needed for computing the ranges from both the Earth Station and Monitor Station was provided by INMARSAT approximately once per week. The measurements used to determine the clock offset at each calibration step were the C/A code pseudo-ranges collected at the NIST Monitor Station.

$$C\_A^{MS} = R_L^{MS} + c * \delta\tau_{Cal} + \delta n_{PR} \qquad \textbf{(1)}$$

where C_A^{MS} = the C/A code pseudo-range measurement at the NIST Monitor Station (MS)
R_L^{MS} = true range between the MS and the INMARSAT satellite
c = speed of propagation of electromagnetic waves in a vacuum
$\delta\tau_{Cal}$ = group delay calibration
δn_{PR} = pseudo-range (PR) noise

If R_L^{MS} represents the true range between the MS and the satellite, then the range computed from the Keplerian elements provided by INMARSAT (R_{Comp}^{MS}) can be expressed as

$$R_{Comp}^{MS} = R_L^{MS} + \delta R_{OE}^{MS} \qquad \textbf{(2)}$$

where δR_{OE}^{MS} is the component of the INMARSAT orbit error in the computed range. Using this in equation (1), the measurement residual is formed by the differences between the measured and computed ranges.

$$\delta R_{Res}^{MS} = C\_A^{MS} - R_{Comp}^{MS} = c * \delta\tau_{Cal} - \delta R_{OE}^{MS} + \delta n_{PI} \qquad \textbf{(3)}$$

The UTC offset of the HP clock at the Earth Station (ES) can be estimated by averaging over the C/A code PR measurement residuals

$$_{orr} = \left\langle \frac{\delta R_{Res}^{MS} + \delta R_{OE}^{MS} - \delta n_{PR}}{c} - \delta\tau \right. \qquad \textbf{(4)}$$

where $\langle\cdot\rangle$ denotes the time average over the measurements.

As can be seen from the above equations, the accuracy of the clock offset estimate is biased primarily by the uncorrected group delay difference between the Earth Station and Monitor Station, and the orbit error in the INMARSAT reference orbit. The effect of the PR noise will be insignificant if averaged over a long enough period.

$$\delta\tau_{Corr} = \frac{\langle \delta R_{Res}^{MS} \rangle}{c} + \frac{\langle \delta R_{OE}^{MS} \rangle}{c} - \langle \delta\tau_{Ca} \qquad \textbf{(5)}$$

The orbit error and calibration terms represent corrections to the residuals. If not accounted for, then the estimate of the ES clock offset will be biased by these amounts. For example, an orbit error on the order of 3 km will result in a bias of about 10 µsec.

Range data was collected at both the Southbury Earth Station and the NIST Monitor Station. The data was collected in roughly two 1-week segments beginning on December 22, 1993 and running through January 6, 1994. The modeled ranges and range-rates were computed from the Keplerian orbital elements for AOR-West to determine the measurement residuals needed for estimating the clock offset and for examining possible orbit errors. The average range from NIST to AOR-West is about 39,500 km and varies by about ±182.5 km from the mean. At Southbury, the average range to the satellite is about 37,900 km and varies by about ±195 km from the mean. The range-rate at both sites is about ±13 m/s.

The range residuals were computed by taking the differences between the measured C/A code pseudo-ranges (modulo 4 msec) at a given site and the ranges computed from the Keplerian elements. The Keplerian elements provided by INMARSAT operations in London, were used in Matlab algorithms to compute satellite positions at the measurement times. These positions were used with nominal site coordinates to compute the theoretical ranges for computing the residuals. Pseudo-range measurements were collected at 1-minute intervals at each site and spanned a period of 14 days, beginning on December 22, 1993.

Figure 5 shows the residuals (mod 4 msec in meters) for the data collected at NIST over the 2-week period (with a 1-day gap). Although a new set of Keplerian orbital elements was available on a weekly basis, the residuals were computed using a single set of Keplerian elements to avoid inducing "jumps" which might mask any inconsistencies in the continuity of the measurements. These residuals have a mean offset of -19.1 m (-0.06 µsec) and a standard deviation of 1895.5 m (6.32 µsec). Obvious diurnal and longer scale features can be seen in the residuals, strongly indicating the presence of orbit errors. The steady increase in the amplitude is also an indication of the degradation of the orbital elements over the 2-week period.

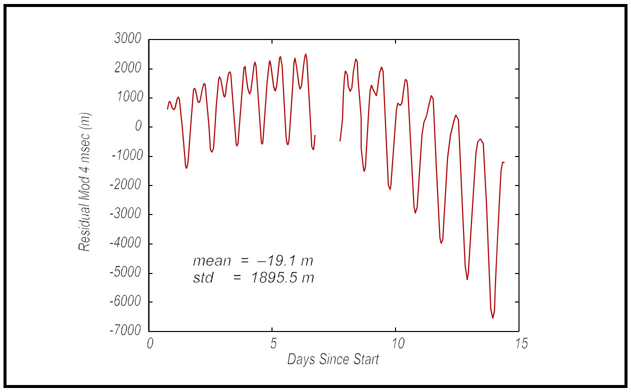

Figure 5 Residuals for NIST Data

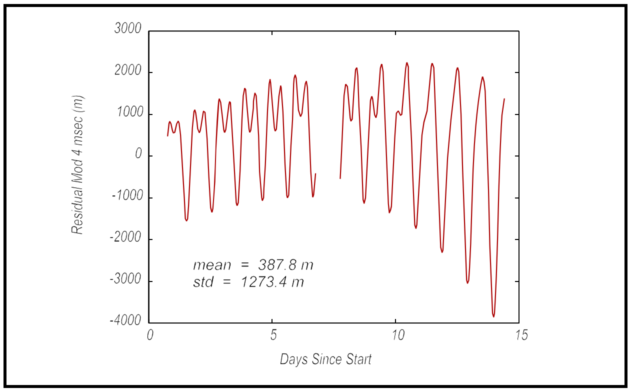

Figure 6 Residuals for Southbury Data

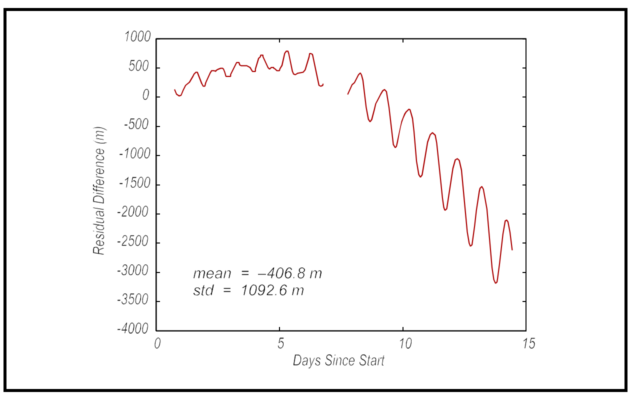

Figure 7 Residual Differences

Figure 6 shows the residuals (mod 4 msec in meters) for the Southbury data of the same period. The same set of Keplerian elements was used to compute these residuals. The mean offset is 387.8 m (1.29 μsec) with a standard deviation of 1273.4 m (4.25 μsec). These residuals also show some evidence of a diurnal feature implying orbit error and a gradual increase in error amplitude.

The data of Figure 5 and Figure 6 were differenced to examine the reduction due to errors common to both sets. The result is shown in Figure 7. A quadratic is apparent in the difference, with residual oscillations having a period of about once per day. The mean of -406.8 and standard deviation of 1092.6 m (3.65 μsec) imply some reduction of a bias.

A further examination was needed to determine the degree of reduction in the oscillatory component of the data. For both sets of data, an orbit adjustment would remove most of the orbit error from these residuals leaving lower order errors attributable to other sources. To examine the magnitude of the oscillatory errors and demonstrate the amount of improvement possible, the residuals in Figure 5 and Figure 6 were filtered and the filtered residuals were removed from the raw residuals. Plots of the filtered data are shown in Figure 8 and Figure 9 for the NIST and Southbury sites.

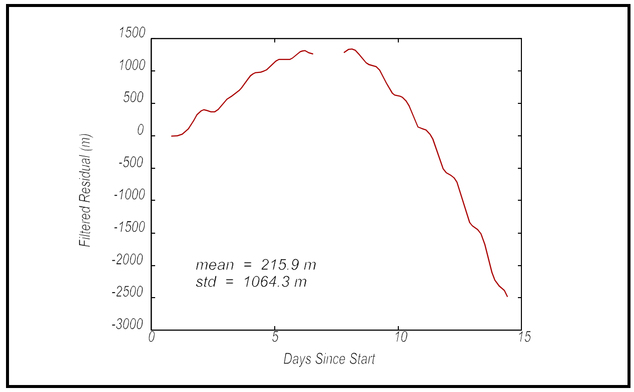

Figure 8 NIST Filtered Residuals

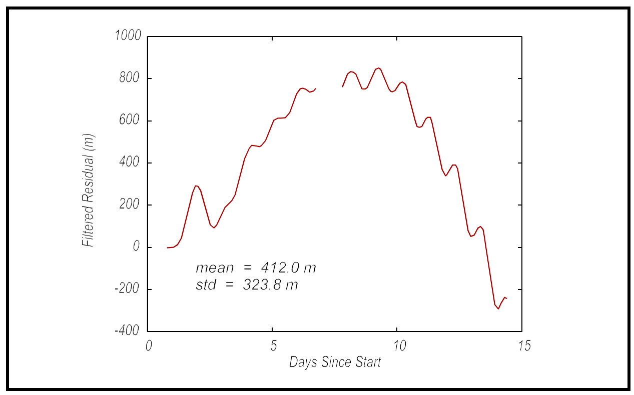

Figure 9 Southbury Filtered Residuals

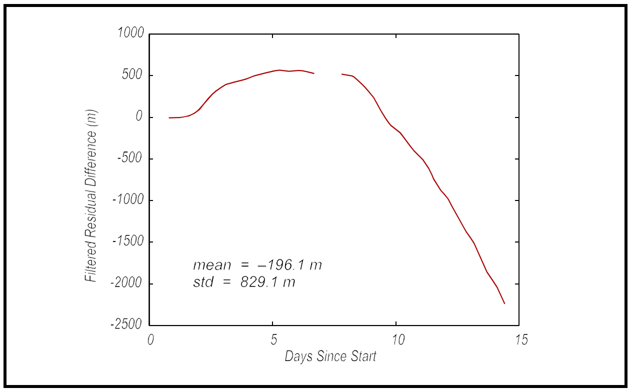

Figure 10 Filtered Residual Differences

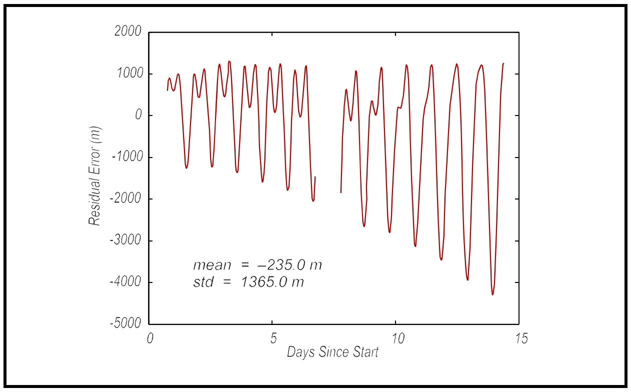

Figure 11 NIST Error Residuals

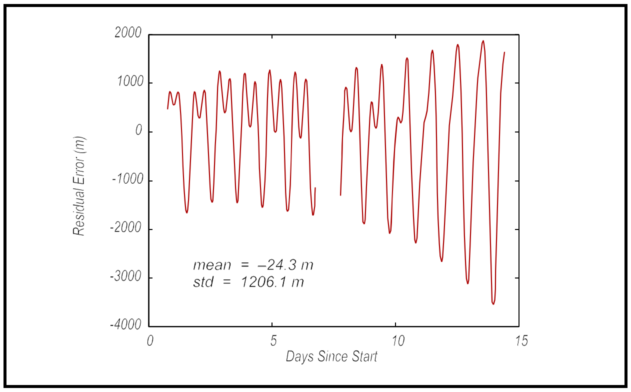

Figure 12 Southbury Error Residuals

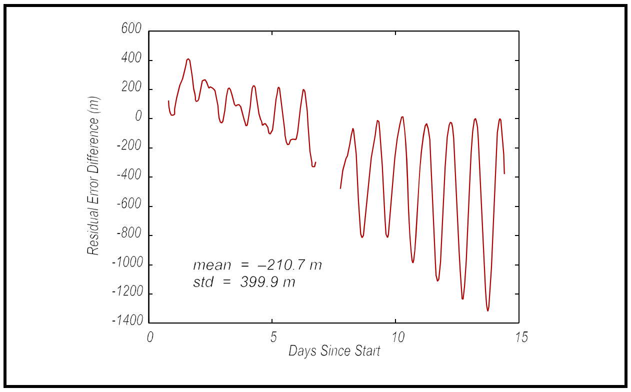

Figure 13 Error Residual Differences

The plot in Figure 8 shows the filtered residuals for NIST which has a mean of 215.9 m (0.73 μsec) and a standard deviation of 1064.3 m (3.55 μsec). The plot in Figure 9 for the filtered Southbury data shows a mean of 412.0 m (1.37 μsec) and a standard deviation of 323.8 m (1.08 μsec). The difference between the NIST and Southbury filtered residuals is given in Figure 10 and retains the quadratic feature with a mean of -196.1 m (-0.65 μsec) and a standard deviation of 829.1 m (2.77 μsec). The differences could be geometric in nature, since each site "sees" slightly different error vectors.

One might expect that since the same Keplerian elements were used to generate the theoretical ranges for both sets of residuals, some components of the orbit error might be common to both sites. Once the filtered "quadratic" components are removed from the residual data, the resulting "error" residuals, given in Figure 11 (NIST) and Figure 12 (Southbury), show clearly the diurnal and semi-diurnal oscillatory components. The NIST residual errors have a mean of -235.0 m (-0.78 μsec) and a standard deviation of 1365.0 m (4.55 μsec), while the Southbury residual errors have a mean of -24.3 m (-0.08 μsec) and a standard deviation of 1206.1 m (4.02 μsec). Both are consistent with orbit errors on the order of a few km in magnitude on the range data. Finally, the differences between the residual errors are shown in Figure 13 and have a mean of -210.7 m (-0.70 μsec) and a standard deviation of 399.9 m (1.33 μsec). A reduction in the standard deviation by a factor of 3-4 over that of Figure 11 and Figure 12 is realized. The remaining oscillations might be due to some combination of the differences in station location/geometry and errors in the station coordinates, although the increasing amplitude again implies degradation of the orbital elements and, hence, the presence of residual orbit error.

CONCLUSION

The testing to date has demonstrated that the IGO system is synchronized to an accuracy of 1 μsec. Periodic orbital errors on the order of ±2000 m (7 μsec) prevented the full system accuracy to be tested.

In the next phase of testing, a precise orbit for the satellite will be determined by combining data from multiple monitor stations. Data will be collected from NIST in Boulder, the Southbury Earth Station, and the University of Leeds, UK. This will be used to compute the precise orbital elements and calibrate the HP 5071A reference at the earth station. In order to achieve nanosecond timing accuracy, the orbit must be determined to meter level.

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